

Appendix B Case Histories

Section I

Ice Harbor Lock and Dam, Downstream Navigation Lock Gate Replacement

B-1. Background

Ice Harbor Lock and Dam is located on river mile 9.7 on the Snake River, near Pasco, Washington. Placed in service in 1962, the navigation lock is 205 704 mm (675 ft) long and 26 213 mm (86 ft) wide. Gates in the lock consist of an upstream tainter gate and a downstream overhead vertical lift gate. This case history describes structural failures and replacement of the downstream overhead vertical lift gate.

B-2. Original Design and Construction

The overall size of the lift gate is 26 822 mm (88 ft) wide by 27 737 mm (91 ft) tall, and it weighs approximately 612 349 kg (675 tons). Normal operating static head on the gate ranges from 29 566 mm (97 ft) to 31 394 mm (103 ft). The gate consists of 18 welded tied arches spanning the navigation lock width, with the skin plate welded to the upstream face. Vertical spacing of the arches is approximately 1045 mm (3 ft 5 in.) at the bottom and increases to 2530 mm (8 ft 3 in.) at the top of the gate. Each tied arch has an upstream curved compression member composed of WT 460x223 (ST 18WF150) welded to the skin plate and a W 840x359 (33WF240) downstream straight tension tie. The downstream tension ties are laced with WT 180x22.5 (ST 7WF15) diagonal and vertical bracing. At the gate's center span and approximately 4570 mm (15 ft) from each end, a diaphragm plate is welded to the arch and tension tie the full height of the gate. Two lifting points are symmetrically placed at approximately 2605 mm (8 ft 6 in.) from the ends of the gate. The gate is operated by two hydraulic hoists, one on each side of the lock, located in concrete towers above the gate. Twelve 60-mm-(2-1/4-in.-) diameter wire ropes, connected on each side of the gate, wrap over a pinion-driven bull gear on a drum and connect to a counterweight that travels vertically in the tower and lock monolith. Plate 1, main text, represents framing of the existing gate.

B-3. Structural Failures

The first documented structural failures began in April 1980 when cracking occurred in the second tension tie from the bottom and adjacent tension ties through the fifth tie at each diaphragm connection. At the end diaphragms the cracks were present in the flange of the tie and entered the diaphragm plate, and in the center diaphragm the cracks propagated through

both flanges and into the web. There were no documented repair procedures; however, repairs consisted of welding cover plates over the cracks in the flanges. Cracks did not appear again until June 1992 when four large cracks were observed and later repaired near the bottom of the gate, at the vee, the intersection of the tension tie girder, and the upstream arch compression member. From 1980 to 1992, the only other incidences of repairs were the the hoisting drum bearings, gear boxes, shafts and hydraulic units in 1989, and in 1991 replacement of guide roller with a compressible shoe. After new cracking developed in 1992, additional cracks were found in August 1993, some located at intersections of diagonals and tension tie girders, others at the vee. Figures B-1 and B-2 represent the typical location of the cracks where holes were recommended for drilling to stop the crack propagation. All were in the lower part of the gate. Because project forces could not keep up with the numerous cracks and crack growth between scheduled outages, a construction contract was required to finish the welding cracks during a scheduled 2-week outage in March 1994. Results from a three-dimensional finite element model of the gate indicated that the diagonal bracing contributed to out-of-plane bending in the tension tie girders, hence increasing the stress in the flanges. Therefore, part of the welding contract required that all diagonal and vertical bracing be removed, with all gouges and sharp edges ground smooth. After the welding was completed, cracking continued. By May 1994, 80 cracks had developed on the gate. Where bracing was removed, the cracking decreased; however, the incidence of cracking at the middle and upper levels of the tension tie girders increased. By June 1994 the total number of cracks increased to 130, almost all on the downstream flange of the tension tie girder. To provide a margin of safety to the integrity of the gate, gussets were added at the vee in the lower six tied arches to reduce high stress. They were designed to carry a portion of the arch load, bypassing a crack in the flange in the vee.

B-4. Corrective Actions

Throughout the time from June 1992 until the lock was placed out of service in December 1995 for replacement of the gate, repair of the numerous cracks continued. Some holes were drilled at the tip of the crack; however, this proved ineffective.

a. Investigations. Investigations were performed to determine the stress level in the member of the gate, metallurgical components of the steel, and any relationship between crushing of the side roller and induced high stresses.

(1) Stress levels. Stress levels in the gate were determined by a three-dimensional finite element model, with instrumentation used for verification and investigation of strains during hoisting, filling, and emptying operations. The first strain monitoring included investigation of strain in the tension ties through various cycles of gate operation. Strain

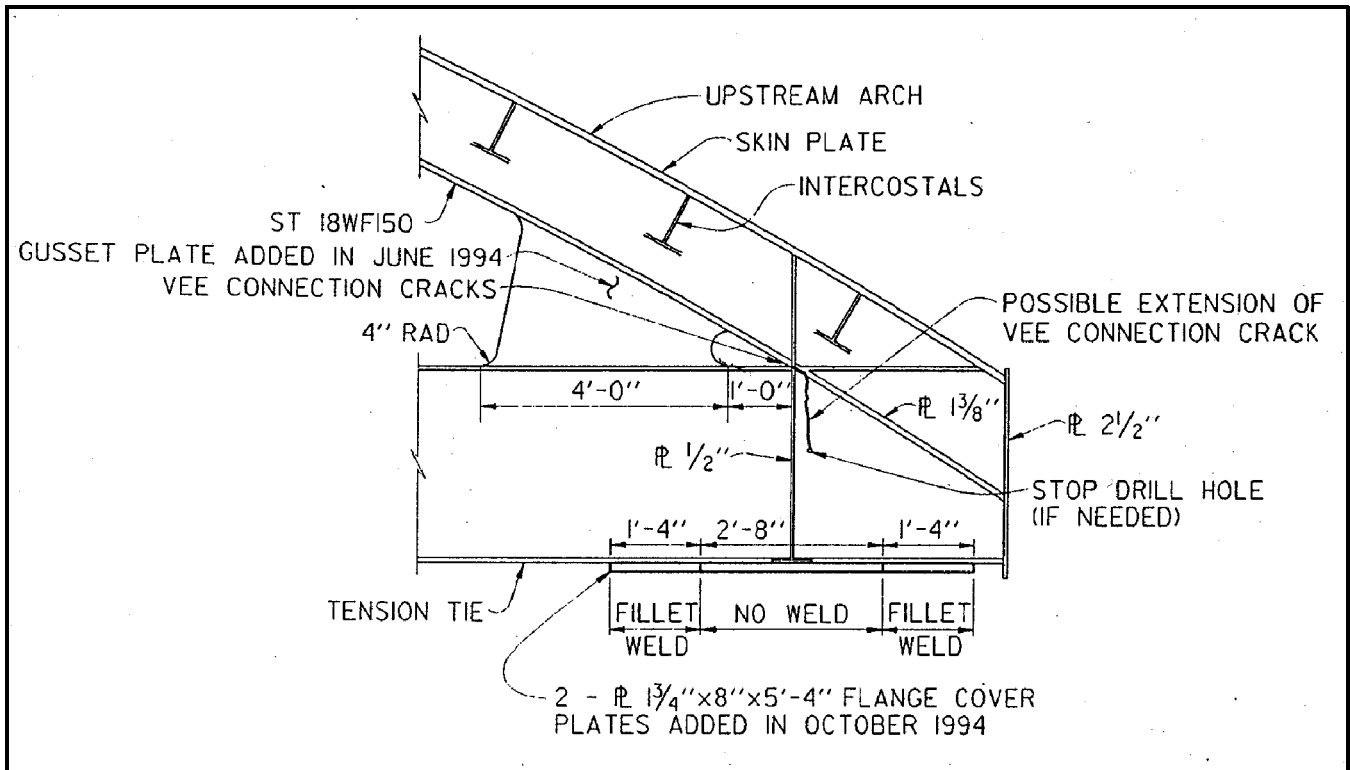


Figure B-1. Vee connection cracks and addition of gusset plate and flange cover plate for the existing gate

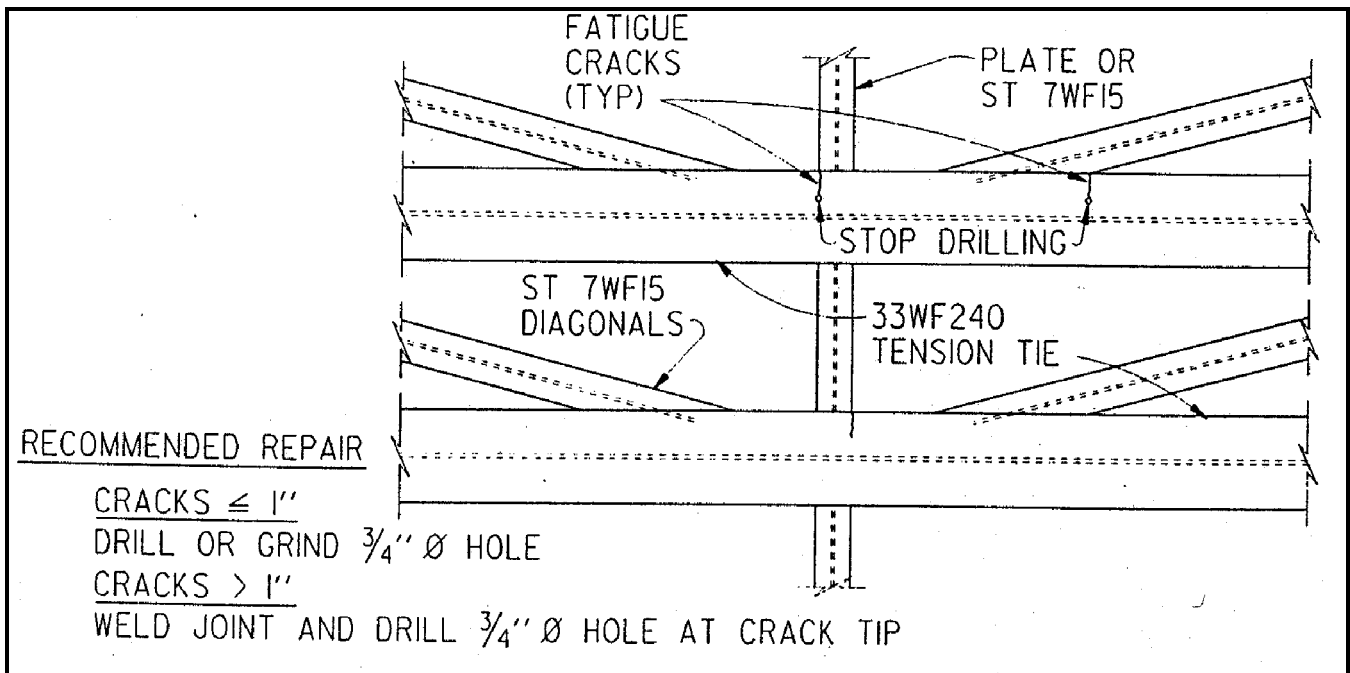


Figure B-2. Typical cracking located at downstream bracing to tension tie flange

monitoring revealed that during the gate's movement a very high stress in the lower tension ties occurred while the gate was raised a short distance. The largest stress was in excess of 372 MPa (54 ksi). No hydrostatic loads were placed on the gate during this operation. Because of this it was theorized that the gate motion was being restrained. During normal hydrostatic loading the stress range was 138 to 206 MPa (20 to 30 ksi), which was expected. To simulate the results that occurred during the gate's movement, various boundary restraints and hoisting loads were applied to the finite element model. The model could not simulate the loading indicated by the strain gauges, nor did pressure gauges in the hydraulic hoisting equipment indicate any overload due to restraint of the gate. To provide more conclusive data to verify computer analysis, and because side roller crushing could still be a factor in gate operation, a second series of strain monitoring was performed with a different contractor. These data indicated that stresses in the tension ties, diagonals, and compression arch were reasonable and similar to the results found in the computer model. No high stresses were reported during the raising and lowering of the gate. Therefore field instrumentation verified findings in the computer model.

(2) Metallurgical. Metallurgical analysis was performed on a coupon cut from the gate across an existing crack. Its chemical composition, hardness and microstructure were consistent with an ASTM A572/A572M, Type 2, Grade 345 (50), high-strength low-alloy steel (ASTM 1994a). This did not comply with the ASTM A242/A242M-93A (ASTM 1993) specified in the original contract. Results from Charpy V-notch tests did not indicate a problem related to low toughness of the steel. Examination of the fracture revealed an instantaneous overload tension failure. The primary failure mechanism was attributed to fatigue.

(3) Other investigations. In order to verify if the gate was restrained during raising and lowering, three separate tasks were performed. The first was an underwater camera inspection of the guide slot. This revealed a worn area on the north guide slot where the bearing shoe had rested. No irregularity existed in the guides. The second was a diver inspection, which involved taking measurements between guide slots, checking the width and depth of each slot, and visually inspecting the guide slots and bottom sill. There were no significant findings. The final was a field survey of the gate. Surveyors gathered three-dimensional coordinate data of the four corners of the gate at various elevations to determine if the gate translated or rotated during its operation. There were no significant findings.

b. Findings of investigations. The tension tie girders experienced a significant amount of cracking on the upstream flange near the vee. Numerous cracks formed on the downstream flange at the diaphragm and downstream bracing. Virtually all cracks start at the tip of welded joints. The

frequency of cracking accelerated to a point that keeping the gate functional for lockages was becoming impossible. Factors contributing to the cracking included the following:

(1) The heat-affected zone at the vee created large residual stresses that may have led to crack development. The vee connection creates a high stress zone due to its geometry.

(2) The welded joints were typically in an AISC fatigue category E. Most of these joints experienced between 172- and 221-MPa (25- and 32-ksi) tensile stresses under hydrostatic loads. The gate experienced approximately 60,000 cycles over 30 years since placed in service. Many of the joints in the gate met or exceeded their expected fatigue life.

(3) The quality of the welds made during the original fabrication were suspect.

(4) Undercutting, backing bars left in place, improper weld rods, and quenching hot steel were typical procedures used in repairs before 1992.

(5) The downstream diagonal bracing members contributed to secondary stresses. These were induced by temperature variations within the gate and residual forces created by frequent welding.

(6) There was no conclusive evidence that the gate was being restrained during raising and lowering.

B-5. Design and Construction of New Gate

All of the findings identified during the investigation of the existing gate were accounted for in the design of the new gate. The material, type of joints and gate configuration, weldments, fabrication, and installation contributed to the new design. Of major consideration was the type of joints as they relate to fatigue. AISC category E was avoided at all costs. Several gate configurations were considered for the replacement, including a miter gate. The miter gate was dropped from consideration due to the extreme cost differential to modify the lock monoliths. Framing options included tied arches, bowstring trusses, and plate girders. The tied arch was the most economical and the simplest to fabricate and was selected for design. Plate 2, main text, represents configuration of the replacement gate.

a. Design and structural configuration. Considered in the preliminary design was the type of connections, particularly revising the vee to a radius, to eliminate high stress risers at the connection of the arch to the tension tie. The preliminary design phase was used to develop connections and construction methods that would eliminate connections in high fatigue categories. By using a flat plate for the tension tie, rather than

a rolled or plate girder, and providing a continuous plate with a radius at the inside corner, category E connections could be avoided. Figure B-3 represents the structural configuration for connection of the compression arch to the tension tie. Preliminary member sizing was performed using hand calculations. Final design was performed using a three-dimensional finite element analysis. A refined model of the connection of arch to tension tie was performed to determine the radius required and resultant stresses. The general gate model consisted of 8,931 three-dimensional single-order quadrilateral shell elements and 1,506 three-dimensional beam elements. Because of large, out-of-plane friction forces that develop under hydrostatic load, stress analysis of the end post (plate) was performed using three-dimensional solid elements. The final design included tension ties consisting of 50- by 686-mm (2-in. by 2-ft 3-in.) plate lying flat, with vertical bracing at 3353-mm (11-ft) intervals. Vertical bracing and hydrostatic loads were resisted with a plate girder located at the top spanning the width of the gate. The skin plate was 32 mm (1 1/4 in.) thick with intercostals spanning the arch plates in the upper third of the gate. The arch consisted of 38- by 610-mm (1-1/2 in. by 2-ft) plate. Loads were transferred to end bearing plates in the concrete through an 89-mm- (3-1/2-in.-) thick end post (plate). Side rollers were replaced with a compressible shoe to eliminate crushing of the steel

rollers that had occurred on the existing gate. Other structural replacements included new wire ropes, new 305-mm-(12-in.-) diameter stainless steel lift pins, and additional concrete ballast and support plates for the counterweight.

b. Material. ASTM A572/A572M, Type 2, Grade 345 (50) steel (ASTM 1994a) was selected based on material toughness, strength, availability, and weldability. The higher strength steel helped reduce the overall weight of the gate, which was a consideration for using the existing hoisting equipment. This provided a significant cost savings in the overall design of the gate.

c. Gate operation. The existing drum, bull wheel, and hydraulic drive system remained in place. The existing selsyn drive was modified to include a zero backlash speed reducer and couplings, along with new limit switches.

d. Fabrication. Because the gate was 27 432 mm (90 ft) high by 26 670 mm (87 ft 6 in.) wide, the gate was fabricated in three sections. Individual sections of the gate were welded in the fabricator's yard, barged to the site, and erected in the gate slot. Because most of the welds in the tension tie and arch were considered fracture critical, welding procedures, including welder qualifications, joint preparation,

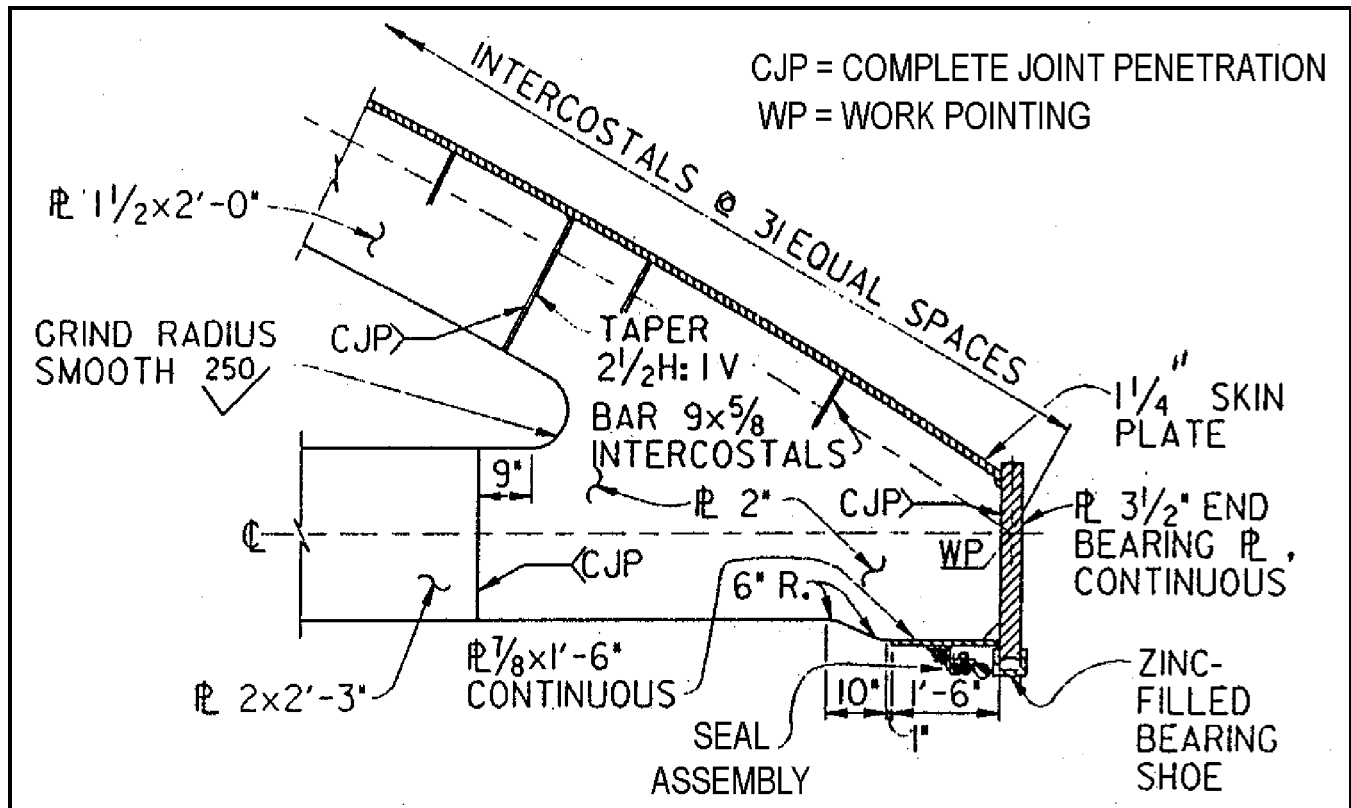


Figure B-3. Connection of compression arch to the tension tie and end bearing plate for the replacement gate

electrode type, and pre- and post-heating temperatures followed AWS D1.5-96 (AWS 1996a). The design was modified during construction to require a full penetration weld joining the gate section skin plate and end post. Scheduled lock outage for the erection of the gate was from 1 January to 29 February 1996, which was extended to 9 March 1996.

e. Corrosion. Corrosion protection for the gate uses a paint system for its primary defense, with cathodic protection applied at the top of the gate where painted mild steel plates connect to a stainless steel pin and cables. Other areas for corrosion potential are where stainless steel bolts were used for connecting seal angles to the gate and seals to the seal angles. All mild steel surfaces are painted. The seal angle mounting detail was revised to provide a neoprene gasket between the stainless steel seal angle and the gate. This will help prevent leakage as well as provide a separation from the two dissimilar metals.

Section II

Locks No. 7, Upstream Gate, Downstream Gate Leaf Replacement

B-6. Background

Locks No. 27 are located on the Chain of Rocks Canal (which bypasses the Chain of Rocks stretch of the Mississippi River) at Granite City, Illinois. Construction of the locks was completed in 1953. The locks consist of a main lock, 365 760 by 33 528 mm (1,200 by 110 ft), and an auxiliary lock, 182 880 by 33 528 mm (600 by 110 ft). The lock gates consist of vertical lift gates at the upstream end and miter gates at the downstream end of the locks. Prior to the addition of a low-water dam at the Chain of Rocks on the Mississippi River in the early 1960's and a subsequent raise in pool elevation at Locks 27, alterations were made to the lift gates to accommodate the higher head caused by the addition of the low-water dam.

B-7. Original Design and Construction

Each lift gate consists of two welded structural steel leaves that span the width of the lock chamber. Each gate leaf is 9144 mm (30 ft) high. A skin plate on the upstream side of each gate leaf forms the vertical damming surface. Plate girders transfer horizontal loads acting on the skin plate to the reactions at the lock walls. The top girder of the upstream gate leaf forms a horizontal damming surface, with pressure from the upper pool acting on the top surface and pressure from the lower pool acting on the bottom of the girder. The bracing on the downstream side of the gate leaf between the girders forms a truss to support vertical loads. Sealed buoyancy chambers are intended to be watertight and provide a reduction in vertical load. Chains and associated machinery, located in

recesses in the lock walls at each end of the gate, adjust the elevation of the gate leaves. The upper gate leaf (downstream gate leaf) is operated (lowered and raised) for each lockage. The lower gate leaf (upstream gate leaf) is operated infrequently, only to adjust for varying pool elevations. Plate 4, main text, shows gate geometry. For large hydrostatic heads, which occur at minimum upper pool levels, the upstream gate leaf is required to be supported on the gate rests at the bottom of the lock.

B-8. Structural Failures

Severe cracking in the upstream gate leaf was discovered in March 1989 during an unrelated construction contract at the main lock. Under normal conditions, the upstream gate leaf is submerged and is not visible. An inspection of the gate leaf revealed numerous cracks in the girders and bracing, adjacent to connections, on the downstream face of the upstream gate leaf. Additionally, all buoyancy chambers were found to be flooded. It is believed the cracking was a result of fatigue as the gate leaf had undergone approximately 250,000 loading cycles at that time. Additionally, almost all of the numerous downstream bracing connections were fatigue category E or E' according to AISC Appendix K (AISC 1995). As part of the alterations in 1960, additional vertical members were added to the downstream bracing, and cover plates were added to the tension flanges of the girders. The connections for these members resulted in additional category E' fatigue details.

B-9. Corrective Actions

Because the damage was considered to be severe, an emergency contract was written for initial repairs to the gate leaf so that the lock could open as planned for the unrelated construction contract. After completion of the initial repairs, a plan of action for permanent repairs was established. The plan involved material testing, review of the original structural computations, placement of strain gauges on the gate leaf, and an in-depth structural analysis using a three-dimensional computer model. Frequent inspections of the gate leaf were conducted while permanent repairs were being considered.

a. Initial repairs. The intention of the initial repairs was to return the gate leaf as much as possible to its original condition while permanent repairs were being considered. Cracks in girder flanges were gouged and fastened using full penetration welds. Cracks in girder webs were gouged and welded closed. The crack tips were located using dye penetrant and a 25.4-mm-(1-in.-) diameter hole was drilled at the crack tip; the holes were left open. Gusset plates were used where the downstream bracing members tied into the horizontal girder flanges to stiffen the joints and to facilitate the repair. Weld repairs were nondestructively examined.

b. Material testing. Samples of material from the original construction contract and alteration contract were removed and tested. Plate, angle, bar, and weld material were tested. The following tests were performed:

(1) Charpy V-Notch. This test provides an indication of a material's ability to absorb energy, which is directly related to toughness (a material's ability to resist crack propagation). The data from the testing for all samples indicated that this material had poor toughness compared to historical data for similar material.

(2) Tensile. Tensile tests were performed to determine yield strength, ultimate strength, and percent elongation. The yield strengths varied from 200 to 241 MPa (29 to 35 ksi) (the material was ASTM A7.) Elongation values were appropriate.

(3) Chemical analyses. Chemical analyses determined the percentage of 10 different elements. These analyses provided information that was used to evaluate two aspects concerning the weldability of the material: the susceptibility to underbead cracking and the potential for heat-affected zone cracking. The carbon content was found to exceed the limit for ASTM A7. As carbon content increases, a material will tend to behave in a more brittle manner.

(4) Micro hardness survey and Brinell hardness. Brinell hardness tests (ASTM 1996e), along with micro hardness surveys and chemical composition tests, provided information to evaluate the susceptibility to cracking. The test data showed that all samples had hardness values below the maximum suggested limiting values to assure satisfactory performance against underbead cracking and heat-affected zone cracking, thus indicating the material was satisfactory in this respect.

(5) Fracture analysis. A fracture analysis of a crack located in the angle was performed to determine additional information concerning how the crack developed. The fracture analysis revealed that the fracture was of a fatigue nature due to one-way bending and low to moderate overload in an area of concentrated high stresses.

c. Original structural computations. The original and alteration design computations were obtained and reviewed to determine what assumptions were made so they could be compared to the actual operating conditions. The gate leaf was analyzed using hand methods. Vertical water loads and dead loads (which included ice and mud loads) were assumed to be divided equally between the skin plate on the upstream face and the bracing on the downstream face. Horizontal loading was assumed to be transferred from the skin plate to the horizontal girders. It was further assumed that the three vertical diaphragms prevented differential loading between girders and caused the gate to deflect uniformly in the

horizontal direction. It was also assumed that the downstream bracing prevented local buckling of the downstream girder flanges as well as supporting the vertical load. The downstream bracing was assumed to act as five separate trusses, stacked on top of one another. Each truss was assumed to carry a portion of the total vertical load, the portion being the ratio of the panel height to the total gate leaf height. Buoyancy chambers located in the bottom two truss panels were designed to provide a buoyant force of 50 percent of the total gate weight.

d. Structural analysis. An in-depth structural analysis of the gate leaf using a three-dimensional computer model of the upstream gate leaf was conducted. The purpose of the analysis was to determine member stresses. A three-dimensional finite element model was used to analyze the gate leaf. Bending and stretching (6 degrees of freedom) elements were used to represent the skin plate, girder webs, buoyancy chambers, end framing, and reaction girder web. Beam elements were used to represent the girder flanges, skin plate intercostals, downstream bracing, chain girder, reaction girder flanges, and apron braces. The model consisted of approximately 600 nodes and 1,300 elements.

(1) Instrumentation. Because of the complex nature of the structural analysis of the lift gate, it was felt that some indication of service stress would be helpful in determining the validity of some assumptions concerning the analysis. Strain gages were placed on several downstream bracing members. For the original loading cases, the strain gages indicated member forces much higher than those indicated by the structural analysis. These data indicated a problem with the loading and/or the structural model. These were later investigated and corrected in the computer analysis, and better agreement was obtained.

(2) Conclusions from structural analysis. The controlling load condition was found to be a combination of the case added to account for the removal of the seal at the sill (removed in the 1960's in an attempt to abate vibration of the gate leaf) and the case added to account for the ineffectiveness of the buoyancy chambers. For the case of no seal at the sill, the net pressure varied from full net horizontal pressure at the top of the sill to zero net pressure at the bottom of the gate leaf (Figure 3-5, main text.) The results of the analysis using the loading cases described above showed improved agreement between overstressed members and members with observed failures, and also improved agreement with strain gage information. The results of the analysis indicated that the gate leaf underwent bending in both vertical and horizontal directions, not just horizontal bending as was assumed in the original computations. Bending in the vertical direction caused an increase in compression in the downstream bracing for certain loading conditions.

(a) Improper assumption of load distribution. It was apparent that horizontal loading of the lift gate had a greater effect on member forces in the downstream bracing than was believed by the original designers. The original designers believed all horizontal loads were distributed to the girders through the vertical diaphragms and the downstream bracing prevented only local buckling of the girder flanges under horizontal loading. However, it was clear from the computer analysis, and substantiated by the strain gage testing, that the lift gate acted as a unit under load with the downstream bracing affected by the distribution of the horizontal load. The additional compression in the downstream bracing face, caused by vertical loads due to water and weight of the gate, combined with horizontal loads resulted in overstress in the downstream bracing members.

(b) Omission of important load case. The original designers did not consider a load case for the buoyancy chambers zero percent effective while the gate was supported on the chains. During the gate repairs many of the chambers were found to be filled with water. The additional vertical load of the water in the buoyancy chambers caused further overstress in the downstream bracing members.

(c) Operating procedures. For higher heads the gate leaf should be supported on the gate rests at the bottom of the lock. Lock personnel identified that the gate leaf had been routinely supported on the chains for conditions when hydrostatic head exceeded the limiting value. This was due to conflicting information given in the operating manual and tolerances in the gate position indicating equipment. This contributed greatly to high stresses in the downstream bracing as indicated by the computer analysis of this loading condition.

(d) Modeling technique. The original designer's assumption of truss behavior of the downstream bracing members is unconservative. Furthermore, the gate was fabricated with many eccentric joints. Both of these items introduced bending moments into the downstream bracing members, which increased the stress. The simplified assumption that the downstream bracing behaved as a truss was made necessary by the crude analysis tools available at that time.

e. Final conclusions. Based on the results from the material testing program, structural analysis, and other information obtained, at least five factors, discussed below, contributed to the cracking of the gate. Based on the cost of repairs and the fact that much of the gate leaf would still have deficient material and welds, the final district recommendation was to replace the upstream gate leaf of the main lock lift gate.

(1) Defective material. The material used to fabricate the gate and the material used for the alterations made to the gate in 1960 both had very poor toughness relative to similar

material being produced presently. These materials did not have the ability to resist crack propagation once a crack initiated from overstress or fatigue.

(2) Design assumptions. Some of the original design assumptions concerning load distribution, load cases, and modeling technique were unconservative. This resulted in actual member stresses (as indicated by the computer analysis and instrumentation) higher than those predicted in the original design. In addition, the bracing connection details were fatigue category E and E' according to AISC (1995) Appendix K, and no consideration was given to fatigue in the design.

(3) Operating procedures. The operating procedures were such that under certain conditions the gate was not on the supports for some loading conditions, as assumed in the design. This resulted in additional load in the bracing. The limit switches for the gate leaf have since been reset to account for tolerances in the gate position indicating equipment to prevent the condition from occurring again.

(4) Fabrication procedure. There was no evidence of low hydrogen welding practice. This is poor practice considering the alterations to the gate leaves in 1960 were made during the winter months. These practices made the welds susceptible to cracking. Also many of the welds were undercut, which reduced the cross-sectional area of the bracing and caused stress risers and susceptibility to cracking. Approximately 90 percent of the welds connecting the downstream bracing to the girder flanges were found to be deficient (did not meet AWS (1996a) bridge specifications) by an independent testing laboratory that performed an inspection as part of the repair contract. In addition to undercutting, the welds did not meet AWS (1996a) profile and porosity requirements. The deficient welds were repaired during the initial repair contract.

(5) Corrosion. As cracks initiate and begin to propagate, corrosion occurs at the crack tip and reduces the critical stress intensity factor, thus promoting crack growth. Corrosion also causes reduction in the net area of members, resulting in increased stresses.

B-10. Design and Construction of New Gate Leaf

The five factors identified in the investigation of the existing gate leaf as contributing to the cracking of the gate leaf, as well as altering the structural configuration, were considered in the design of the new gate leaf.

a. Material toughness. For adequate material toughness a minimum toughness requirement for all members was written into the specification. To minimize gate weight, ASTM A572/A572M Grade 345 (50) steel (ASTM 1994a) was used. Deflections were considered and kept within acceptable limits.

b. Design assumptions. A three-dimensional finite element model was used for the design of the new gate leaf. Much information concerning overall gate leaf behavior and distribution of loads was obtained, minimizing the number of assumptions necessary. Because of concerns regarding the reliability of buoyancy chambers, they were not used in the new gate leaf. Loading cases generally followed the original gate leaf except for an additional case to account for the missing water seal at the sill.

c. Structural configuration. Similar to the existing gate leaf, the new gate leaf is horizontally framed. The horizontal girder spacing was altered to provide uniformity, which is the most efficient when considering all possible loading conditions. Based on the results of the structural model and gate testing, it was determined that additional vertical diaphragms were necessary. A vertical diaphragm was placed at each panel point. Panel point spacing remains the same as the original gate leaf and corresponds to the spacing of the gate rests at the bottom of the lock. For the downstream bracing, a perforated skin plate was used instead of discrete bracing members. The rounded perforations provide access for inspection as well as a reduction in gate weight. The system of discrete downstream bracing members was flawed in that it was difficult to obtain connections that were not susceptible to fatigue. The skin plate with smooth rounded perforations has very good resistance to fracture and fatigue. All connections throughout the new gate leaf were designed in accordance with AISC (1995), Appendix K. Improving fatigue performance involved stopping transverse stiffeners short of tension girder

flanges, and coping vertical diaphragms so that no contact is made with girder flanges. All joint details were designed so that allowable stress ranges would not be exceeded.

d. Operating procedures. The original gate leaf used float-operated selsyn transmitters to report the position of the gate leaf. This type of device is unreliable for determining if the gate leaf is supported on the rests or on the chains. Hence, operating restrictions with regard to when the gate leaf was required to be on the rests or on the chains could not be met. A system of digital encoders was installed, replacing the original selsyn transmitting equipment. The new system, mounted on the existing chain sprocket, accurately indicates when the gate leaf is supported on the rests or on the chains and therefore ensures that operating restrictions can be met.

e. Fabrication. The majority of the new gate leaf was fabricated in the shop, where conditions are readily controlled. Strict control of welding procedures, including welder qualification, joint preparation, electrode preparation, and pre- and post-heating temperatures, was maintained. Low hydrogen welding practice, in accordance with AWS D1.1 (AWS 1996b), was specified for all welded connections.

f. Corrosion. Elimination of crack potential was a major goal in the design of the new gate leaf; however, should cracking occur during the service life of the new gate leaf, corrosion will be minimized through the use of passive cathodic protection devices mounted at regular intervals.